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by

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16. ABSTRACT The article discusses coal cleaning options for reducing SO2 emissions. (NOTE: There are >500 physical coal cleaning (PCC) plants in the U.S. About 50% of utility coal is cleaned, primarily for ash removal. SO2 emission from the combustion of as-mined U.S. coal may range from <1.0 to >9.0 lb SO2/10 million Btu.) Conventional PCC can reduce the potential SO2 emission from high sulfur coal by 20-50%, depending on the inherent properties of individual coals. SO2 emission reduction by conventional PCC is limited by the amount of finely distributed mineral sulfur (pyrite) and organic sulfur in coal. Advanced fine coal cleaning technologies can be used to remove fine pyrite and sometimes organic sulfur. SO2 emission reductions resulting from advanced coal cleaning processes range from <50% to >90%. Coal cleaning may be used in combination with other technologies to reduce SO2 emission. Combinations such as coal cleaning and limestone injection multistage burners (LIMB) or flue gas desulfurization (FGD) may be more cost effective than FGD alone. The use of a multi-stream coal preparation plant to produce deep-cleaned and middling products is another control option. The deep-cleaned coal, which is low in ash and sulfur, can be burned without further SO2 emission control while the middling product can be burned in a boiler with a LIMB or FGD system.

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Pollution	Pollution Control	13B
Coal	Stationary Sources	08G
Coal Preparation	Coal Cleaning	09I
Desulfurization	Limestone Injection Multistage Burners (LIMB)	07A, 07D
Sulfur Dioxide		07B

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Acid Rain Conference

Coal Cleaning Options for SO_2 Emission Reduction

James D. Kilgroe and Jerome Strauss

Abstract

There are more than 500 physical coal cleaning (PCC) plants in the U.S. Approximately 50 percent of utility coal is cleaned, primarily for ash removal. SO_2 emission from the combustion of as-mined U.S. coals may range from less than 1.0 to more than 9.0 lb $SO_2/10^6$ Btu. Conventional PCC can reduce the potential SO_2 emission from high sulfur coal by 20 to 50 percent, depending on the inherent properties of individual coals. SO_2 emission reduction by conventional PCC is limited by the amount of finely distributed mineral sulfur (pyrite) and organic sulfur in coal. Advanced fine coal cleaning technologies can be used to remove fine pyrite and sometimes organic sulfur. SO_2 emission reductions resulting from advanced coal cleaning processes range from less than 50 to more than 90 percent.

There is no comprehensive up-to-date information on SO_2 emission reductions which can be achieved by washing. An evaluation of 1979 data on utility coal from eight major eastern and midwestern coal producing states indicates that approximately 48 percent was cleaned, reducing potential SO_2 emission by 2.7 million tons (15 percent). If all of the unwashed high sulfur coal from these states had been cleaned with conventional technology, SO_2 emission would have been reduced by an additional 2.0 million tons. Further SO_2 emission reductions by cleaning coal from these states would require the use of advanced technology.

Coal cleaning may be used in combination with other technologies to reduce SO_2 emission. Combinations such as coal cleaning and limestone injection multistage burners (LIMB) or flue gas desulfurization (FGD) may be more cost effective than FGD alone. The use of a multistream coal preparation plant to produce deep-cleaned and middling products provides another control option. The deep-cleaned coal, which is low in ash and sulfur, can be burned without further SO_2 emission control while the middling product can be burned in a boiler with a LIMB or FGD system. An alternative option would be to clean the middling coal with advanced cleaning technology.

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Introduction

Congress is now considering legislative options for controlling the harmful effects of acid depositions. Proposed solutions include those which would require a substantial reduction in SO_2 emission from coal combustion. These solutions would apply primarily to eastern and midwestern coal-fired utility boilers.

Emission reductions ranging from 4 to 12 million tons per year have been proposed. Coal cleaning has been advocated as a method of achieving SO_2 emission reductions. Widely different claims are put forth concerning the ability of coal cleaning to provide reductions in SO_2 emission. In some instances coal cleaning is seen as an option which will forestall the need for scrubbers. In other instances coal cleaning is viewed as having little value. The truth is probably somewhere between these extremes.

The place of coal cleaning in helping to achieve any legislatively mandated SO_2 emission reductions is uncertain. This uncertainty arises from a number of factors:

- The amount, the geographical distribution, and timeframe of reductions is unknown.
- The policies which will be used to allocate and implement reductions are unknown.
- The current level of SO_2 reductions being achieved by commercially operating plants and the potential for further reduction by these and new plants is uncertain.
- The technical potential and cost of using near-term and advanced coal cleaning technology which is being developed for improved SO_2 reduction is uncertain.
- The benefits of using cleaned coal to reduce boiler operation and maintenance costs are largely unknown.

The first two factors relate to policy decisions which will be made on the basis of technical, economic, social, and political considerations. We will not attempt to deal with these first two factors, but will be content with the more manageable but still difficult task of analyzing the technical potential and benefits of coal cleaning.

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The intent of this paper is to:

- Describe the manner in which the inherent properties of coal limit the removal of sulfur and ash by conventional techniques.
- Provide an understanding of methodologies which can be used to clean coal.
- Provide an overview of current coal cleaning practices.
- Provide information on the costs and benefits of cleaning coal.
- Provide estimates of SO_2 emission reductions which can potentially be achieved by state-of-the-art and advanced technologies.
- Illustrate how coal cleaning can be used in conjunction with other technologies to provide SO_2 emission reductions.
- Summarize industry trends and barriers to expanded use of coal cleaning.

Technology overview

An understanding of the potential and limitations of coal cleaning in reducing SO_2 emission requires a knowledge of coal properties, the technologies which may be used for cleaning, the costs of cleaning, and the cost benefits of cleaning. The following sections provide background information which is essential to understanding the manner in which coal cleaning can best be used in the further reduction of SO_2 emission from coal combustion.

Coal characteristics

Coal is a complex assemblage of materials which originate from past and detrital material deposited in swamps or bogs. In addition to its plant-derived organic constituents (carbon, hydrogen, oxygen, and nitrogen), coal contains significant quantities of minerals and inorganic elements. The relative abundance of the organic and inorganic constituents varies significantly between coals of different types and between different locations in a single coal seam. The variability of coal properties is a function of the environment and chemical

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composition of the coal vegetable matter and the subsequent geological history of the consolidated coal forming material.

The classification of coal by rank provides information useful in assessing its properties as a fuel. The American Society for Testing and Materials (ASTM) classification system includes four classes of coals: anthracite, bituminous, subbituminous, and lignite.(1) The location of coal fields and the rank of coals in these fields are shown in Figure 1.

Coal constituents of primary concern to power engineers and environmentalists are ash and sulfur. Ash is the solid residue which is left from the combustion of coal mineral matter. The quantity and composition of coal ash is used to characterize a coal with regard to its properties as a boiler fuel. It is difficult and costly to determine the mineral content of coal, and the ash content (a much easier determination) is often used as a surrogate. The amount of ash in coal is determined by the amount of solid residue from a laboratory combustion test. The amount of mineral matter in relationship to ash and sulfur can be approximated by the Parr formula:(1)

$$\text{Mineral Matter} = 1.08\ \text{ash} + 0.55\ \text{sulfur}$$

The in-seam mineral content of U.S. coals as determined by ash analysis ranges from less than 2 to more than 50 percent. There is generally not a strong correlation between coal rank and the quantity and characteristics of the coal mineral matter.

The density or specific gravity of various coal constituents is an important property which is used in separating the organic and mineral components of coal. The specific gravity of various organic components of coal called macerals ranges from 1.2 to 1.7. The specific gravity of coal minerals, such as clays and carbonates, generally ranges from 1.7 to 2.2. The specific gravity of pyrite, the principal sulfide mineral in coal, is 5.0.

The sulfur content of U.S. coals ranges from less than 1 to more than 7 percent. Sulfur is contained in three principal forms: mineral sulfur, organic sulfur, and sulfate sulfur. Mineral sulfur, generally in the form of pyrite (FeS_2), can range from microscopic inclusion in the coal to large mineral fragments several inches in size. Organic sulfur, comprising from 30 to 70 percent of the

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total sulfur content of most U.S. coals, is an integral part of the coal matrix and can only be removed by chemical modification of the coal structure. Sulfate sulfur is present in very small amounts and can usually be removed by water washing of coal.

There is no direct relationship between the coal sulfur content and coal rank. The relative amount of sulfur and its distribution into different sulfur forms is dependent on the coal depositional environment and succeeding geological events such as the geologic events which deposited the roof material and controlled the percolation of ground water through the coal seam. While there is no direct causal relationship between the sulfur content and rank of coals, geological events in the U.S. resulted in lignite, subbituminous, and anthracite coals with low to moderate amounts of sulfur. The sulfur content of U.S. bituminous coals may range from low (<1 percent) to high (>3 percent).

Potential cleaning methods

The two most important unit operations used in coal preparation are size reduction and the subsequent separation of the organic and mineral components of run-of-mine (ROM) coal. Size reduction through breaking or crushing generally causes the coal to fracture along the boundaries between the organic structure and extraneous mineral components. The degree to which the mineral components are liberated is dependent on the coal properties, the size reduction techniques, and the degree of size reduction. Crushing the coal to fine particle sizes liberates more mineral particles; this may hinder or help subsequent separation processes.

Coal cleaning can be defined as the classification of coal particles by differences in the physical, chemical, or electrical properties. Physical coal cleaning technology involves a wide variety of separating phenomena which depend on the properties of the particles (size, shape, density, or surface properties), the properties of the separating medium (density, viscosity, etc.), the type of cleaning equipment, and the operating conditions of the cleaning equipment. Chemical coal cleaning technology uses chemical reagents or bacteria to selectively remove mineral or organic components from the coal structure. Electrical separation depends on differences in the electrostatic or electromagnetic properties of the coal particles. Although chemical and electrical separation

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processes are being developed, none of these processes are used commercially in the U.S.

Washability analyses

Laboratory washability analyses are standardized tests which are used to assess the sulfur and ash reduction potential of coal by physical separation techniques. Washability is a function of the inherent properties of a specific coal and washability test technique. The primary test technique of interest in this paper is that used for specific gravity separations.

The potential for reducing the ash and sulfur content of a coal by specific gravity separations is determined by laboratory tests called float-sink tests.(1,2) In these tests, a coal sample is crushed and separated into various size ranges. Each size fraction is float-sink tested in organic liquids of standardized specific gravity. The weight, percent ash, heat content, total sulfur, and (sometimes) pyritic sulfur content of each density and size fraction are then determined (Table 1 is an example). These data are used to determine the mineral and desulfurization potential and specify the design and operating conditions for physical coal preparation equipment.

Desulfurization potential of U.S. coals

The desulfurization potential of U.S. coals by commercial coal cleaning techniques can be estimated from the float-sink data collected by the Bureau of Mines (BuMines) and Department of Energy (DOE). The merged BuMines and DOE data base now contains washabilities on more than 900 U.S. coal samples.

The effects of crushing and specific gravity of separation are "qualitatively" similar for nearly all coals. The weight recovery (yield), energy recovery, ash content, and sulfur content decrease with decreasing specific gravity of separation. At low specific gravities, only those particles which are relatively free of embedded pyrite or mineral particles will float. Coal particles containing moderate amounts of mineral and pyrite particles sink along with pure mineral particles. This produces a cleaner product but at the expense of high energy losses to the sink (i.e., refuse) fraction.

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Crushing the coal to finer particle sizes liberates a higher fraction of the mineral and pyrite particles from the organic coal structure. This results in improved separation of the mineral and organic components during the subsequent float-sink tests. The general effects of coal particle top size and specific gravity of separation are shown in Figure 2.

Both the ash and sulfur reduction potential is important in assessing the potential reduction in SO_2 emissions by Federal regulations. Federal regulations specify an emission limit or percentage reduction relative to the heating value of fuel burned (i.e., lb $SO_2/10^6$ Btu). Coal cleaning reduces the SO_2 emission in amounts which are proportional to the reduction in the sulfur and ash level between the raw and cleaned coal. The reduction in ash increases the fuel heating value and diminishes the amount of fuel necessary for a specific amount of power generation. Even if the sulfur content of the fuel is unchanged, the reduced fuel requirement which results from the higher heating value reduces overall SO_2 emissions. The SO_2 emission parameter in lb $SO_2/10^6$ Btu will be used to designate the potential heat specific SO_2 emission which would result if all the sulfur contained in a coal were converted to SO_2 on combustion.

Estimates on the average emission reduction potentials of U.S. coals are presented in Table 2. This data which was taken from a 1976 Bureau of Mines report represents weighted averages of 455 coal samples from six coal producing regions.(2) This data is for conditions [crushing to 1-1/2 in. top size and separating at 1.6 specific gravity (s.g.)] which provide clean coal properties which are representative of cleaning conditions in commercial coal cleaning plants. The six coal producing regions are: northern Appalachian (NA), southern Appalachian (SA), Alabama (A), eastern midwestern (EMW), western midwestern (WMW), and western (W).

The average emission and emission reduction potential of coal varies from region to region. It also varies from state to state, from seam to seam within a given state, and even between different locations within the same coal mine.

The average SO_2 emission parameters for raw coal from the northern Appalachian, eastern midwestern, and western midwestern regions range from 4.8 to 9.0 lb $SO_2/10^6$ Btu. After cleaning by crushing to 1-1/2 in. top size and taking a 1.6 s.g. float product, the average SO_2 emission parameter for clean coal from these three regions ranges from

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3.2 to 6.1 lb $SO_2/10^6$ Btu. Although the average reduction in SO_2 emission parameter is about 30 percent for the high sulfur coal regions, SO_2 emission reductions for individual coals may range from less than 20 to greater than 50 percent.

The southern Appalachian, Alabama, and western regions contain mostly low-sulfur coals. The potential SO^2 emission parameters for raw and cleaned coal generally fall in the range of 1.0 to 2.0 lb $SO_2/10^6$ Btu. Some individual low-sulfur coals show little or no sulfur reduction in SO_2 emission parameter when washed. Others show reductions of 25 percent or higher. The average SO_2 emission parameter reduction for cleaning low-sulfur coals is 11 to 12 percent.

The variation of coal washability within a given region or state can be illustrated by float-sink data for three northern Appalachian coal samples (see Table 3). These samples are from the Pittsburgh Seam in Harrison County, Ohio; the Clarion Seam from Meigs County, Ohio; and the Upper Freeport Seam in Westmoreland County, Pennsylvania. The sulfur contents of the Pittsburgh, Clarion, and Upper Freeport raw coal samples are 3.5, 3.5, and 3.6 percent, respectively. The respective emission parameters of the raw coal samples are 5.5, 6.8, and 6.1 lb $SO_2/10^6$ Btu. Differences in the raw coal emission parameters result primarily from differences in the coal ash content, a major determinant of the coal heating value.

By crushing the samples to a 1-1/2 in. top size and separating at specific gravities which will produce a Btu recovery of 95 percent for the Pittsburgh coal, 92.5 percent for the Clarion coal, and 90 percent for the Freeport coal, the respective emission parameters are reduced to 4.3, 4.4, and 2.9 lb $SO_2/10^6$ Btu. This represents emission parameter reductions of 22, 36, and 54 percent. The SO_2 emission parameters for the cleaned Pittsburgh and Clarion coals are virtually identical. The larger reduction in emission parameter for the Clarion coal results primarily from its higher initial ash content relative to the Pittsburgh coal. The outstanding cleanability characteristics of the upper Freeport coal result from the facts that most of the ash and pyritic sulfur is large in size, is liberated from the organic coal matrix by crushing, and is easily removed by specific gravity separation.

The differences in emission parameter values for the three cleaned coals result primarily from differences in the inherent coal proper-

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ties and not the modest differences in the separating specific gravities which were selected to achieve the specified Btu recoveries. If all three coals had been cleaned at 1.6 s.g., then the cleaned coal emission parameters for the Pittsburgh, Clarion, and Freeport coals would have been 4.5, 4.3, and 2.6 lb $SO_2/10^6$ Btu, respectively.

Commercial coal preparation unit operations

Commercial coal cleaning methods are generally limited to operations for the physical preparation of coarse, medium, and fine coal. The largest size or top size of coarse coal may range from 4 to 1-1/4 in. depending on the plant design. The coal size range for modern plants may be considered to be: coarse - 1-1/2 to 3/8 in.; medium - 3/8 in. to 28 mesh; and fine - 28 to 100 mesh. The very fine coal of less than 100 mesh is seldom processed in commercial plants.

The primary coal operations are comminution, sizing, cleaning, and dewatering.

Comminution. The major objective of comminution in preparation plants is to reduce the run-of-mine (ROM) coal to sizes suitable for cleaning and to liberate mineral impurities. In addition, size reduction is usually required to meet the product coal size specification dictated by the market. Major types of comminution equipment used in coal preparation plants include rotary breakers, roll crushers, and hammermills.

Sizing. Coal is sized by screens or hydraulic classifiers. Air classifiers are used by a few facilities. Sizing is used for: (1) separating refuse and fines prior to crushing, (2) separating raw coal into size fractions for further processing, (3) removing fines prior to cleaning, and (4) removing water from coarse and medium size coal particles.

Cleaning. Cleaning is the step in which coal is separated from its impurities. The separation takes place in water, in a dense medium, or in air. Mechanisms for cleaning operations are based either on the specific gravity or on the surface property differences between coal and its impurities. Examples of coal cleaning equipment using water as the separation medium include jigs, concentrating tables, hydrocyclones, and froth flotation cells. Table 4 provides characteristics of major wet-coal cleaning devices.

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A number of criteria are traditionally used to evaluate the performance of state-of-the-art coal cleaning equipment. The various criteria are usually classified according to the degree to which they depend on the properties of the coal being cleaned. The important independent equipment performance criteria are those which characterize the efficiency with which organic and mineral coal constituents are separated.

Important dependent criteria which are often used to characterize plant as well as equipment performance include yield or weight recovery, Btu recovery, ash reduction, sulfur reduction, and emission parameter reduction. All are generally expressed as a percentage of measured value in the coal product divided by the measured value in the coal feed.

Dewatering. Cleaned coal and refuse streams from wet cleaning need dewatering to meet the product specifications and refuse landfill disposal requirements. Excessive moisture in the cleaned coal and refuse is undesirable because it creates handling problems, increases transportation costs, reduces the heating value of the cleaned coal, and increases the boiler fuel requirement.

Moisture can be removed by two types of devices: mechanical dewatering devices and thermal driers. Mechanical dewatering devices can be classified as those that do not produce a final product (e.g., cyclones and thickeners) and those that do produce a final product (e.g., screens, centrifuges, and filters).

Preparation plant design

There are about 560 coal preparation plants in the U.S. These plants are classified by the type of circuit used (jig, concentrating table, heavy medium, etc.). Because of the large number of different circuit combinations, plants are also classified by the degree or intensity of coal cleaning.[3,4,5] Although there are a number of different descriptors and associated definitions of the level of cleaning, the authors prefer to use a system based on the number of different coal size ranges cleaned in separate circuits and the number of product streams. In the following definitions, alternative descriptors which generally apply to similar definitions are shown in parentheses:

Level 0 (Level A, Absence). Coal is shipped as mined.

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Level 1 (Level B, Breaking). Mine debris and large noncombustible impurities are removed. Unit operations include crushing and sizing.

Level 2 (Level C, Coarse Beneficiation). Coarse and medium-size coal is cleaned in a single circuit (usually a jig or heavy media vessel). The fine coal is not cleaned but is either recombined with the coarse and medium coal for shipment or is discarded as refuse.

Level 3 (Level D, Deliberate Beneficiation). In this case, all the feed is wetted, and coarse/medium size coal and fine size coal are washed in separate circuits. All the washed coal is mechanically dried. This cleaning level can involve the exclusion of the fine coal material (the most difficult and expensive to dewater) from the product with separate cleaning circuits for the coarse coal and medium size coal. This process generally results in a low yield and sometimes high cost. Typical Level 3 plants have heavy media washers to clean coarse and medium size coals together plus flotation cells or tables to clean the fine coal.

Level 4 (Level E, Elaborate Beneficiation). The coarse, medium, and fine size coal are cleaned in separate circuits. The coals from these circuits are combined to form a single product. A Level 4 plant may typically have heavy media vessels, heavy media cyclones, and flotation cells to handle the three fractions of coal, respectively.

Level 5 (Level F, Deep or Multistream Cleaning). Coarse, medium, and fine coal are cleaned in a number of different circuits. The coal from the circuits is combined to form two products: a deep cleaned coal and a middling coal. The deep cleaned coal is a metallurgical grade coal or a compliance grade coal which is low in ash and sulfur. The middling coal has a higher ash and sulfur content. A simplified schematic of a Level 5 plant is presented in Figure 3.

Cost of preparation

The cost of coal preparation is a function of level of preparation, percentage of material discarded as refuse, coal washability, and plant size. The preparation costs are dependent on the amount of mineral matter removed and not strongly influenced by the coal sulfur content, except where sulfur reduction is the principal criterion

for design and operation of the plant. Costs for coal preparation can vary widely, and the costs for each plant must be considered individually with respect to location, terrain, coal properties, preparation specifications, and coal production rate.

Total capital investment for a 1000 ton/hr plant may range from $20 to $90 million (January 1985 dollars).(6) This consists of direct and indirect costs. About one-third of the total direct cost is attributed to the FOB cost of cleaning equipment. The remainder of the direct costs are associated with equipment installation, coal receiving/storage/loadout, coal preparation prior to cleaning, and other on-site facilities. Indirect costs included in total capital investment include engineering, overhead, and project contingencies, and these make up about one-third of the total capital investment.

The capital cost of a plant increases somewhat as the level of cleaning increases, but there is considerable overlap in the capital costs of plants of different cleaning levels.

Annual cost preparation costs include: material costs, operating and maintenance expenses, overhead, and capital charges. Amortization costs and the costs of material mined and discarded as refuse have the greatest effect on annual costs. Amortization accounts for 10 to 40 percent of the annual costs, and cost of mined and discarded materials may account for 15 to 70 percent. Total annual costs are often expressed in terms of $/ton of cleaned coal, the value added to the coal product by preparation. For a 1000 ton/hr plant, the costs of preparation, excluding discarded material, may range from $2.00 to $4.60/ton depending on the level of preparation.(6)

For smaller preparation plants, the annual costs of preparation are increased because of the economics of scale achieved in large plants. Including the costs of coal rejects (assuming material mined costs of $25/ton), total annual costs can range from $3.50 to $20.00/ton.(6) In the worst case the coal is of poor quality and more than 40 percent of the mined material must be discarded as refuse.(7) Although preparation adds substantially to the costs of these coals, they probably could not be sold unless they were cleaned.

Benefits of coal preparation

The benefits derived from coal preparation are in three general areas: coal handling, coal combustion, and emission control.(4,8,9)

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In many instances coal cannot be marketed unless it has been cleaned. This is true if the coal seam has partings or is mined by techniques which result in significant amounts of out-of-seam dilution material (roof and floor material).

Transportation and handling cost reductions occur if the coal is prepared at the mine site. Preparation reduces the ash content of the coal and increases its energy value. This reduces the amount of coal needed to meet boiler energy requirements, thereby reducing coal transporation costs and the costs of coal handling at the power plant.

Of the reasons advanced for the use of cleaned coal, perhaps the greatest single benefit (other than the control of emissions) is in the area of boiler fireside performance. Fireside problems result in forced and scheduled outages. They significantly affect the cost of boiler operation and maintenance, the capacity factor, and the availability of the generating facility. By modifying the coal characteristics that contribute to these problems (e.g., slagging, fouling, and corrosion) coal preparation can favorably affect the economics of coal use. Typical cost benefits from improved boiler operations are estimated at $2.60/ton of cleaned coal (O&M - $0.45/ton; availability - $2.05; boiler efficiency - $0.10), but can range from $0.50/ton to as high as $8/ton.(6) Recently representatives of several major utilities reported that increased boiler availability and reduced maintenance costs alone may justify a switch to cleaned coal.

Coal preparation reduces ash disposal costs, since both bottom ash and fly ash amounts decrease when cleaned coal is burned. However, particulate control equipment may not function as efficiently with this cleaner fuel, particularly electrostatic precipitators, requiring gas conditioning to meet particulate standards. On the other hand, several studies have shown that in many cases the combination of coal preparation and flue gas desulfurization (FGD) is less costly than FGD alone. Coal preparation, by removing 30 to 40 percent of potential SO_2 emissions, may allow partial scrubbing of flue gases rather than full scrubbing to meet emission regulations.

Advanced coal cleaning processes

Conventional coal preparation technology suffers from two major shortcomings. First, it is ineffective for the removal of organic

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sulfur, most fine-grained mineral matter, and pyritic sulfur from coal. For this reason, the maximum amount of ash and sulfur that can be removed by this technology from a given coal is primarily limited by the predominant grain size of pyritic sulfur and mineral matter in coal. Second, it is not efficient in cleaning fine and very fine particle size coal. Various advanced coal cleaning processes are being developed to overcome these shortcomings.(10)

Advanced processes based on physical and electrical techniques can remove more pyritic sulfur than conventional technology, but they are ineffective for the removal of organic sulfur. Chemical cleaning processes which use chemical or biological agents (bacteria) remove mineral sulfur and sometimes organic sulfur, depending on the process.

Improved sulfur removal is achieved by grinding coal to finer sizes to enhance greater liberation of pyritic sulfur and mineral matter and to increase the specific surface of the coal particles for reaction. However, advanced coal cleaning processes are more expensive than the conventional coal preparation technology because of the costs associated with grinding the feed coal, dewatering and drying the wet coal (for wet processes), and storing, handling, and transporting the fine product. Costs of wet processes can be reduced if the cleaned coal is designed for use in a slurry form.

Table 5 lists major advanced coal cleaning processes and the organizations involved in their development. It also provides information on the sulfur removal method, the types of sulfur removal, and relative time period needed for commercialization.

Trends and barriers

Recent changes in the coal and utility industry encourage the preparation of a larger percentage of eastern and midwestern utility coals. These include: higher coal prices and transportation costs; diminishing coal quality due to less selective mining techniques, reduction of easy-to-mine coal reserves; the need to increase availability and capacity factors at existing boilers; stringent air quality standards; and lower costs for improving fuel quality versus investing in extra pollution control equipment.(10,11,12) In addition, recent projections show a 4.4 percent growth rate in production of Northern Appalachian coals which benefit from coal cleaning. Midwest-

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ern coal, which is very amenable to cleaning, is forecasted to have a production decline until 1990, then grow at an average rate of 3.9 percent a year.(13)

Discussions with coal and utility industry personnel support the relatively optimistic outlook for coal preparation. They believe the increase is likely because:

- Acid rain legislation may force utilities to burn moderately lower sulfur coals.
- High ash content of many ROM coals are pushing utilities toward cleaning to meet boiler specifications.
- Current research on the benefits of cleaning is expected to indicate considerable savings to utilities.
- Tight markets are forcing coal companies to offer better fuel products to be competitive.

Counter arguments to increased cleaning reflect continuation of current conditions including: increased availability of low sulfur eastern and western coals; stable oil prices; decreased metallurgical coal demand; and a reduction in orders for new coal-fired units.

Much of the future demand for clean coal can be absorbed by current idle capacity in the preparation industry. Coal consumption continues to reflect low growth conditions. Utilities continue to cancel or defer construction of new coal-fired boilers. For each 1000 MW of new generating capacity that is delayed, about 3 million tons of coal is not produced and cleaned. In most coal producing regions, in the past few years, there have been periods when the only coal that was being sold was contract coal or coal that was drawn off stockpiles at below cost prices. In an effort to boost demand for cleaned coal, two states - Ohio and Kentucky - have funded studies of advanced coal cleaning processes and of ways to promote the cleaning process.

To compete in today's coal market, most large coal companies are cleaning high and medium sulfur coals and improving mining techniques. Several industry representatives have stated that they are investigating modifications at all their preparations plants in order to

offer better products to their customers. Blending the good quality and poorer quality coal at the preparation plant is becoming common practice to produce an average coal blend that meets product specifications.

Barriers to expanded coal cleaning can be removed by:(11,14)

- Better quality control in cleaning.
- Improved techniques for separation of fine pyrite.
- Data on the benefits accruing to boilers.
- Better control of leachate from solid wastes.
- More information on sulfur removal potential.
- Monetary incentives to use or produce clean coal (i.e., tax considerations).

In addition, uncertainty surrounds current legislation and regulations, such as the Clean Air Act, potential acid rain legislation, and the effluent guidelines requirements for preparation plants. Some coal industry representatives are quite pessimistic about the future of coal preparation, especially in the established eastern and midwestern coal fields. They believe that factors such as the thinning of mineable seams, the financial instability of many small mining companies, increased environmental costs, and higher bonding requirements do not bode well for the future of many small mining companies.(10) It is believed by many that the situation in the coal industry will only improve once oil prices put alternative fuels and feedstocks in a competitive position, a condition that may be 15 to 20 years away.

If acid rain legislation is passed, requiring lower SO_2 emissions, then certain technical trends will probably occur within the coal preparation industry. These would be:

- An increased use of heavy medium circuits operated at lower specific gravities to optimize sulfur and ash removal.
- More intensive fine coal cleaning.

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- Use of multi-stream plants producing low sulfur coals for combustion without pollution controls and high sulfur coals to be burned with pollution controls (e.g., FGD, fluidized bed boilers, LIMB).

- Greater plant automation to increase productivity and product standardization.

Overall, utilities are not against using clean coal, they just do not have sufficient information (nor do the state public utility commissions) about its advantages to include cleaning benefits in fuel choice decisions. If information is available to show that cleaning coal to produce a better quality fuel will actually lower busbar costs in spite of the increase in fuel costs, then the utility industry will have the incentive to use clean coal. An EPRI spokesman has stated, "Integrated planning and economic studies from coal base to busbar are essential if the coal producer is to adequately cover his capital investment in improving coal quality with a reasonable return." In summary, there is a great need for teamwork between the coal and utility industries, their suppliers, and regulatory agencies if electricity is to be produced in the most cost-effective way.(11)

Cleaning options for reducing SO_2 emissions

Estimates of further SO_2 emission reductions via coal cleaning require a knowledge of the reductions which are now being achieved by commercial practice and the potential emission reductions which are technically and economically achievable by further cleaning. Unfortunately information bases on the application of current coal cleaning methods are incomplete, and estimates concerning the technical potential and costs of advanced technologies must be considered to be speculative. Nevertheless, an understanding of the technical potential and limitations of coal cleaning for SO_2 reduction can be achieved by an examination of current knowledge.

Proposed legislative initiatives designed to reduce acid deposition require a reduction in SO_2 emission as referenced to some base year. Reductions ranging from 4 to 12 million ton/yr have been proposed. A wide range of control options, including fuel switching, coal cleaning, flue gas desulfurization (FGD), and limestone injected multistage burners (LIMB), have been discussed. Coal cleaning can be used either

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by itself or in conjunction with other technologies such as FGD or LIMB. The following sections will discuss SO_2 emission control options involving coal cleaning. The use of these options will be illustrated by cases involving the Pittsburgh, Clarion, and Upper Freeport coal samples which were previously discussed.

Options which incorporate the use of coal cleaning may incorporate either state-of-the-art or advanced technologies. Options which appear to be the most logical include:

State-of-the-Art

1. Blending cleaned coal with naturally occurring low sulfur fuels.

2. Burning cleaned coal from a single product preparation plant without SO_2 emission controls.

3. Burning cleaned coal from a single product plant in a boiler system containing additional SO_2 emission controls.

4. Burning the deep cleaned coal from a multi-product plant in a boiler without SO_2 emission control and burning the middling product in a boiler with or without additional SO_2 emission control.

Advanced Technologies

1. Burning cleaned coal from a single or multiple product plant in boiler(s) without further SO_2 emission controls.

Blending cleaned coal with low sulfur coal is a technically and economically viable approach to reducing SO_2 emission from coal combustion. The costs of this approach will depend on the delivery costs of the cleaned and naturally occurring low sulfur coal and the costs of blending. Wide adoption of the approach would substantially impact low sulfur coal and transportation costs because of supply and demand factors. These factors are beyond the scope of this paper and use of strategies involving low sulfur and cleaned coal blends will not be attempted.

The conventional technology approaches which use more than one generic type of SO_2 emission control technology are defined here as

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combined approaches. Physically cleaning coal in a single product plant and burning it in a boiler with an FGD is an example of a single stream combined approach. Burning the middling coal from a multi-product plant in a boiler with FGD is an example of a multi-stream combined control approach.

Advanced coal preparation plants which incorporate both conventional physical coal cleaning methods and advanced coal cleaning techniques are not considered by the authors to be combined approaches, even though both traditional and advanced technologies will probably be used in advanced plants. Combined approaches which incorporate both advanced coal cleaning technologies and boiler-related SO_2 emission control technology are not believed to be economically competitive with the other approaches and were not listed under logical approaches for advanced technologies. These approaches will not be discussed.

Single stream state-of-the-art options

Single stream state-of-the-art coal preparation plants employ many different design and operating conditions. The design and operation of the plant are in turn based on the washability of coal(s) being processed. Laboratory washability data such as that developed by DOE[2] can be used to estimate the performance of commercial plants in cleaning coals of varying cleaning potential.

EPA studies have shown that laboratory wash float product data for coal crushed to 1-1/2 in. top size and separated at 1.6 s.g. underpredicts the reduction of ash and sulfur which is achieved by cleaning similar coals in commercial plants.[15] Some of this difference, which is generally not great, results from the fact that the DOE data are based on coal face sample taken directly from the coal seam. Floor and ceiling material are not included in this sample. Commercial preparation plants clean ROM coal which often contains substantial amounts of floor and roof dilution material. Removal of this extra dilution material accounts for the increased ash and sulfur reductions at actual plants, as compared with the DOE laboratory washabilities.

An important use of the washability data is that it allows comparisons between coal products which result from different cleaning con-

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ditions. For example, suppose that the Pittsburgh coal with washability properties summarized in Table 1 must be cleaned to provide a product capable of meeting an SO_2 emission regulation of 3.6 lb SO_2/ 10^6 Btu. Table 1 shows that, by crushing the coal to a 1-1/2 in. top size and by separating at 1.4 s.g., a clean coal with a 3.6 lb $SO_2/10^6$ Btu can be obtained. However, Table 1 also shows that only 79.7 percent of the coal energy (Btu recovery) results for this cleaning condition. Further examination shows that, by crushing the coal to a top size of 3/8-in. and by separating at 1.6 s.g., a product with the desired emission parameter is obtained. At this latter condition 95.1 percent of the coal energy is recovered. This latter condition avoids excessive coal losses and is a more economical approach.

Examination of Table 1 shows that a product with an emission parameter of 3.6 lb $SO_2/10^6$ Btu can also be obtained by crushing the coal to 14 mesh and separating at 1.9 s.g. This condition provides 97.1 percent Btu recovery of the laboratory float product. However, commercial plants do not now process all their coal at these fine particle sizes, and to do so would result in a substantial increase in costs.

Alternative strategies for determining the design and operating conditions of a plant would be to specify a coal with minimum ash content or specify a plant with minimum Btu recovery. The estimated performance data provided in Table 2 was based on Btu recovery criteria. Clean coal properties for conditions other than those given in Table 1 are obtained by plotting the washability data and by determining the cleaned coal properties from the washability curves.

The single stream SO_2 emission reductions shown in Table 2 are representative of many other high sulfur coals from the northern Appalachian and eastern midwestern coal producing regions. The single stream cleaning options illustrated in Table 2 can in general be applied to other coals with the use of washability data.

Conventional multi-stream technology

The multi-stream approach is a method of segregating cleaned coal into two or more product streams. No commercial plants in the U.S. produce more than two product streams. The origins of the multi-stream coal cleaning method are found in the metallurgical industry

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where one deep-cleaned product stream is produced for metallurgical coal and a middling product is produced for the steam coal market.

The best known application of the multi-stream approach is the multi-stream coal cleaning strategy (MCCS) plant which was designed to provide compliance coals for the Homer City Power Station.(16) The Homer City coal cleaning plant was designed to produce a middling coal for two 600 MW units which must meet an emission limit of 3.7 lb $SO_2/10^6$ Btu and a deep cleaned coal for one 650 MW unit which must meet an emission limit of 1.2 lb $SO_2/10^6$ Btu.

A schematic of a simplified multi-stream approach is shown in Figure 4. This simplified flow sheet will be used in conjunction with washability data from Pittsburgh, Clarion, and Upper Freeport seams to illustrate some possible applications of multi-stream coal cleaning strategies. The actual designs of multi-stream plants are much more complex.

As shown in Figure 4, ROM coal is separated at some high specific gravity to form an intermediate product. This separation is set in our examples at conditions required to give an overall plant Btu yield--95, 92.5, or 90 percent. The sink portion of this separation is discarded as refuse and the float product is again separated at a low specific gravity--in this case 1.35. The properties of the middling and deep-cleaned products from this separation are summarized in Table 6. In each case, most of the coal ends up in the deep-cleaned product. The Btu recovery in the deep-cleaned products ranges from 65 to 76 percent. The quality of the deep-cleaned products are very high relative to the raw coal since a disproportionate amount of the ash and pyritic sulfur has been segregated in the middlings. In fact, the emission parameters for the middling products illustrated in Table 6 are 23 to 40 percent higher than the emission parameters for the raw coal.

The quality of the final middling product can be improved and its quantity increased by reblending it with some portion of the deep-cleaned coal. For example, the final middling and deep-cleaned product streams may be designed for equal Btu recovery. If the overall plant were designed for a 95 percent Btu recovery then each of the final product streams would provide a 47.5 percent Btu recovery.

The properties of the blended middling and deep-cleaned products for equal Btu recovery on the Pittsburgh, Clarion, and Upper Freeport

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coals are presented in Table 7. The emission parameters for the deep-cleaned products range from 1.8 to 3.5 lb $SO_2/10^6$ Btu while the emission parameters for the blended middling products range from 3.9 to 5.5 lb $SO_2/10^6$ Btu. The reduction in emission parameter ranges from 43 to 71 percent for the deep-cleaned product--values which are substantially better than for the single product plant. On the other hand, the reduction in emission parameter for the middling products ranges from 1 to 36 percent.

For the cases illustrated here, the average reductions in emission parameter for the multi-stream plants are the same as the emission reductions for the corresponding single stream plants. Although the multi-stream plant is more complex, resulting in higher cost products, this cost disadvantage may be more than compensated for when two products of substantially different quality are required such as at the Homer City Power Station. The multi-stream plant also allows for another option in which the deep-cleaned coal is burned in a boiler without further SO_2 control and the middling coal is burned in a boiler with some SO_2 emission control device such as LIMB or FGD. This option may offer some cost advantages over more conventional approaches as discussed in the following section on integrated control approaches.

Single stream combined technologies

Coal cleaning may be combined with limestone FGD, LIMB, lime spray dryer FGD, or other technologies. However, the crucial test for combined technologies is the cost relative to competitive single technology approaches. One combined single stream approach for control of SO_2 emission has been widely studied: the combination of physical coal cleaning and limestone FGD (PCC + FGD).[17,18,19,20,21] Other approaches have generally not been studied, and little information on their potential cost effectiveness is available in the open literature. EPA is now studying the potential use of LIMB with physical coal cleaning (PCC + LIMB), and we shall briefly consider combined systems using either LIMB or FGD.

Studies of PCC + FGD indicate that this combined approach is in many (but not all) cases more cost-effective than the use of FGD alone. Studies sponsored by EPA, the Electric Power Research Institute (EPRI), and Department of Energy (DOE) indicate that the least cost control approach depends on many site-specific factors, the most

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important of which include coal properties, cleaning conditions, SO_2 emission regulation, and coal transportation costs.

The cost of PCC + FGD is sensitive to the level of cleaning and the Btu recovery of the preparation plant. In some cases, Level 2 cleaning is more cost effective than Level 4 cleaning. In other cases the reverse is true. Reducing the specific gravity of separation for a given plant design reduces the clean coal emission parameter but also reduces Btu recovery. For Btu recoveries below approximately 90 percent the costs of coal discarded with refuse become excessive, and it is generally more cost effective to obtain added SO_2 control through FGD than through improvements in clean coal quality.

If SO_2 emission reductions of less than 70 percent are required, then FGD cost savings which accrue (in large part from the ability to by-pass flue gas for stack gas re-heat) are often large enough to make the combined approach less costly than FGD alone. For high sulfur coals and standards requiring 90 percent emission reduction, FGD alone may be the most cost-effective approach unless substantial savings are obtained from reduced boiler operating and maintenance and coal transportation costs.

Nearly all previous studies on PCC + FGD evaluated the use of this combined approach for new utility boilers. For new units, the capital costs of FGD are generally amortized over 30 years. Acid deposition control measures involving coal-fired boilers will generally be applied to older units which do not now incorporate FGD systems. For older units which must be retrofit with SO_2 emission control devices, a 15-year period of capital amortization is generally assumed. This shorter amortization period will increase annual costs as compared with new units. Equipment installation costs for retrofit units may also be substantially higher than for new units--in some studies it is assumed that total capital expenses for retrofit units are 40 percent higher than for new units. If coal preparation plant costs are amortized over a 20- to 30-year period (it is assumed that the operating life of a preparation plant need not be tied to the lifetime of existing units), the economics of retrofit applications may greatly favor PCC + FGD. This is especially true if SO_2 emission reductions less than 70 percent are required.

Other combined approaches which use boiler-related SO_2 control technologies less costly than lime/limestone FGD are also of interest. One of the more interesting possibilities is PCC + LIMB.

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The goals of EPA's LIMB program are to develop a retrofit technology capable of producing a 50 percent reduction in NO_x emission and a 50 to 60 percent reduction in SO_2 emission at cost savings of $100/kW compared with limestone FGD. Sulfur capture in pulverized coal-fired boilers can be achieved by injection of calcium-based sorbents into the burner flame zone or upper furnace. High sorbent utilizations are necessary to reduce costs and minimize potential boiler fouling and plugging problems. Pilot-plant data currently show that injection of hydrated lime in the upper furnace will probably provide the utilizations required to meet performance and cost goals while avoiding potential boiler problems.

Preliminary cost studies have shown that combinations of PCC and LIMB can provide a 60 percent reduction in SO_2 emission at a lower cost than LIMB alone. Both LIMB and LIMB + PCC have substantially lower capital and operating costs than FGD and they are generally more cost effective in $/ton SO_2 reduction. If LIMB systems prove capable of meeting the performance objective of 60 percent removal for a wide range of coals, the PCC + LIMB combinations may be capable of attaining greater emission reductions than can be met with LIMB alone.

An example of the potential SO_2 emission reductions which can be obtained when burning conventionally cleaned Pittsburgh, Clarion, and Upper Freeport coals with a 60 percent efficient LIMB system and a 90 percent efficient FGD system is shown in Table 8. The emission reductions for this single stream combined approach range from 69 to 81 percent for the LIMB systems and 92 to 95 percent for the FGD systems.

Multi-stream combined systems

Although multi-stream combined systems have not received much attention, they exhibit the potential for increased flexibility and lower costs in reducing SO_2 emission. The major advantage of the multi-stream combined approach is that the deep cleaned coal can be burned in a boiler without additional SO_2 control devices, while the midling product can be burned in a boiler with some other control device such as LIMB or limestone FGD (see Figure 5). Systems using LIMB in combination with a multi-stream coal preparation plant which incorporates conventional physical coal cleaning technology shall be designated MPCC + LIMB. Multi-stream systems used in combination with FGD shall be designated MPCC + FGD.

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The potential emission reductions and emission levels associated with the use of multi-stream combined systems are shown in Table 9. In developing Table 9 it was assumed that the LIMB process provides an additional 60 percent SO_2 emission control and the FGD process provides an additional 90 percent SO_2 emission control for the blended middling products in Table 7. The emission parameter reduction for the deep-cleaned product depends only on the coal type and is independent of the boiler emission control technology used for the middling product stream.

The emission parameter reductions for the deep-cleaned products range from 43 to 71 percent. When LIMB is used to control SO_2 emission for the middling stream, the final emission from this stream is reduced by 60 to 75 percent, as referenced to the raw coals. The system average SO_2 emission reductions are 51 percent for the Pittsburgh coal, 58 percent for the Clarion coal, and 76 percent for the Upper Freeport coal. The average system SO_2 emission parameters range from 1.7 to 2.8 lb $SO_2/10^6$ Btu.

When FGD is used to control SO_2 emission from the middling stream, the final emission from this stream is reduced by 91 to 94 percent and the system average emission reductions range from 67 to 85 percent. Average system SO_2 emission parameters from the Pittsburgh coal, the Clarion coal, and the Upper Freeport coal are 1.8, 2.0, and 1.1 lb $SO_2/10^6$ Btu, respectively.

Advanced coal cleaning

Advanced coal cleaning technology is that which can be used to clean fine (28 x 100 mesh), very fine (100 x 270 mesh) and ultra-fine (<270 mesh) size particles. These technologies are in an early stage of development and there is little data on the performance of these technologies in cleaning a wide variety of coals. To overcome this problem, we will define some realistic performance goals for a number of different advanced technologies and shall evaluate the reductions in SO_2 emissions which can be achieved by technologies which meet these goals.

Advanced coal cleaning technologies can be categorized as fine coal cleaning (FCC) technologies, very-fine coal cleaning (VFCC) technologies, and chemical coal cleaning (CCC) technologies. The FCC technologies are defined as near-term technologies, while the

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VFCC and CCC technologies require a greater period of time to develop. It is assumed that the real technologies within these categories will be capable of meeting performance goals as follows:

FCC is to be capable of achieving sulfur and ash reductions equivalent to the laboratory washability obtained by crushing coal to a 14 mesh top size and taking a 1.6 s.g. float product.

VFCC is to be capable of removing 90 percent of the pyritic sulfur from the raw coal and reducing the ash content to 4 percent. The moisture-free calorific value of the clean coal product is assumed to be equivalent to a 1-1/2 in. top size washability float product at 4 percent ash. The Btu recovery is assumed to be 90 percent.

CCC is to be capable of removing 95 percent of the pyritic sulfur and 40 percent of the organic sulfur. The ash content of the clean coal product is assumed to be 4 percent and the calorific value of the product is assumed to be equivalent to a 1-1/2 in. top size washability float product at 4 percent ash. A 90 percent Btu recovery is assumed.

By applying these process goals to the washability data for the Pittsburgh, Clarion, and Upper Freeport coals, estimates can be made for the SO_2 emission reductions which can be achieved by a single stream preparation plant which processes all the coal by the advanced technology in question (see Table 10). As expected, the SO_2 emission reduction increases with increased technology level. The emission parameter reductions which are dependent on the coal range from 37 to 71 percent for FCC, 53 to 75 percent for VFCC, and 72 to 86 percent for CCC.

The costs of processing all of the coal with advanced technology may be prohibitive. An alternative strategy would be the use of a plant which integrates conventional and advanced technologies. Conventional technology would be used to perform low specific gravity separations and produce a deep-cleaned product. The middling product would be crushed to finer sizes and processed by FCC, VFCC, or CCC technology. The deep cleaned and advanced technology product streams would be combined to form a single product stream (see Figure 6). Alternatively, the deep cleaned and advanced technology products could be sold separately.

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Estimates of the plant average SO_2 emission reductions which could be obtained by using conventional and advanced technology for coal preparation is summarized in Table 11. These estimates were made by applying each of the advanced technology performance goals to the middling product streams given in Table 6. Depending on the coal, the reduction in emission parameter ranges from 34 to 62 percent for the PCC + FCC plant, 44 to 69 percent for the PCC + VFCC plant, and 51 to 72 percent for the PCC + CCC plant. The emission parameter reductions for these integrated technology cleaning plants are better than for the conventional plants but not as good as for plants using only advanced technology. This difference results mainly from the small fraction of the coals that are processed by advanced technology in the integrated technology plants. The amount of coal processed by advanced technology ranges from 14 to 29 percent by weight depending on the coal (see Table 6). The quality of the final product from the integrated plants could be improved by cleaning a larger fraction of the coal with advanced technology. However, this would result in increased costs.

Comparison of options

The average SO_2 emission reductions which can be obtained with the various options for reducing emission from the Pittsburgh, Clarion, and Freeport coals are summarized in Table 12. The advanced cleaning technologies offer substantial improvements over the conventional coal cleaning plants for reducting SO_2 emission. However, the costs for cleaning all the coal in an advanced preparation plant by a single advanced technology may be prohibitively expensive. Advanced cleaning technologies may cost from 2 to 4 times more than conventional cleaning technologies. Integrated technology plants using both conventional and advanced technologies would provide a more economically viable approach. However, the SO_2 emission reductions achieved by these plants are limited by the fraction of the coal cleaned by the advanced technology. Increasing the fraction of coal cleaned by advanced technology will provide additional SO_2 emission reduction, but at the expense of added costs. The extent to which added costs are acceptable will depend on the costs of other competitive approaches.

The multi-stream combined systems will provide SO_2 emission reductions which are similar to the advanced technology plants: the VFCC and MPCC + LIMB emission reductions are equivalent while the CCC and

MPCC + FGD emission reductions are equivalent. However, there are substantial performance and cost uncertainties associated with VFCC and CCC, and the multi-stream approaches may prove to be more viable.

A comparison of the potential SO_2 emission reduction which can be achieved by various coal cleaning options is useful in that it provides information concerning the technical limitations of coal cleaning and offers insight into additional knowledge which must be acquired to assess the various alternative emission control methods. The performance goals assumed for the FCC, VFCC, and LIMB systems are believed in most cases to be technically achievable, but the costs of attaining these goals are unknown. For example:

1. The near-term performance goal for advanced coal cleaning technology can be achieved by crushing coal and by performing gravimetric separations. However, a plant has never been designed and operated to achieve these goals. There are major uncertainties in the costs of dewatering, drying (if needed), and handling of fine coal. There is also some technical uncertainty in being able to assume performance goals for integrated plants where the middling product is crushed to fine size and recleaned. For some coals it may be necessary to crush the middling coal to very fine sizes to achieve sufficient liberation of ash and sulfur to meet the implied performance goal. If this is true, then the multi-stream approach would necessarily have to incorporate VFCC technology.

2. The VFCC goal represents a technical limit for non-chemical coal cleaning technology. It is probably technically possible to liberate 90 percent of the pyritic sulfur from most coals by sufficient size reduction. The costs of providing cleaned product involving minus 100 mesh, minus 270 mesh or even minus 325 mesh coal will be high. The equipment capital costs may be high, and poor separation efficiencies may result in poor Btu recovery and attendant high operating expenses. Dewatering and handling of the fine coal will further increase costs.

3. A number of chemical coal cleaning processes appear capable of removing 95 percent of the pyritic and 40 percent of the organic sulfur. This percentage reduction in organic sulfur may incur substantial process energy penalties. The costs of chemical reagent generation, coal-reagent separation, coal dewatering,

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and pollution control add substantial costs to the overall process. The relative cost of chemical coal cleaning, in comparison with competing technologies such as LIMB and FGD, is uncertain.

4. Advanced coal cleaning technologies will provide fuels low in ash and sulfur. In some cases, this can provide substantial savings in boiler operating and maintenance costs. The current state of knowledge does not permit an accurate estimate of these potential cost savings. These cost savings should be incorporated into site specific studies during evaluation of least cost strategies.

These and many other factors must be considered in further evaluation of various options for reducing SO_2 emission.

Reductions in SO_2 emissions by application of coal cleaning

An EPA study published in 1981 estimated that commercial coal preparation reduced the potential SO_2 emission of coal delivered from eight eastern and midwestern coal producing states in 1979 by 1.8 million tons.(15) These states, Pennsylvania, Ohio, West Virginia, Virginia, Kentucky, Alabama, Illinois, and Indiana, were estimated to have cleaned 33 percent (weighted average) of the coal produced for utility consumption. It was also estimated that if all the coal delivered to utilities from these states had been cleaned with conventional technology, the annual 1979 SO_2 emission would have been reduced by a further 2.9 million tons.

A recent re-evaluation of this study revealed that the percentage of utility coal cleaned in some of the eight states had been substantially underestimated. Data from the DOE Energy Information Administration show that approximately 48 percent of the utility coals from the eight states were probably cleaned in 1979.(23) By applying the revised cleaning estimates to the amount and sulfur content of delivered coal, new estimates were obtained as shown in Table 13. These revised estimates show that the then current cleaning practices probably reduced the annual SO_2 emission by 2.7 million tons, 5 percent more than the previous estimate. As a consequence, the estimates for further potential reductions by washing all coals from these states must be revised.

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Table 14 provides estimates for further emission reductions which could have been obtained in 1979 by cleaning all utility coals produced in the northern Appalachian and eastern midwestern coal regions. Estimates for reducing SO_2 emission by further washing were not included for the regions which produce predominately low sulfur coal. The results of a previous study indicated that cost effectiveness of using conventional coal cleaning technologies for controlling SO_2 emission from high sulfur coals would range from approximately $200 to $400/ton of SO_2 reduction in 1979$, while the costs of cleaning low sulfur coal would range from approximately $500/ton to more than $2000/ton of SO_2 removed. The costs of cleaning low sulfur coal to remove small amounts of sulfur are high and cleaning these coals for the marginal reductions in SO_2 emission is not cost effective.

An analysis of the data in Tables 13 and 14 shows that the relative amounts of coal cleaned, the SO_2 reduction achieved by the current practice, and the potential for further reductions using conventional cleaning technology varies from state to state. For example, the cleaning of 82 percent of Illinois utility coals resulted in SO_2 emission reductions of 950 thousand tons in 1979. The potential for further reduction by cleaning all Illinois utility coals by commonly used technology was 210 thousand tons. By contrast, the cleaning of 42 percent of Ohio utility coals in 1979 resulted in reductions of 330 thousand tons. The potential for further reductions in 1979 by cleaning Ohio coals was approximately 450 thousand tons. The total SO_2 emission reduction achieved by cleaning all utility coals from the entire eight state region was 2.7 million tons, a 15 percent reduction from the potential SO_2 emission of the as-mined coal. If all the unwashed coals from the northern Appalachian and eastern midwestern coal regions had been cleaned with conventional physical coal cleaning technology, the potential SO_2 emission would have been reduced by another 2.0 million tons—a 13 percent further reduction from the as-delivered coal emission.

A crude assessment of the potential impact of using advanced coal cleaning techniques to augment SO_2 emission reductions can be made by applying regional average washability data from Reference 2 to the 1979 coal data provided in Table 13. Three scenarios are considered: PCC + FCC, PCC + VFCC, and PCC + CCC. In each scenario it is assumed that conventional coal cleaning technology is used to clean 75 percent of all the high sulfur coal from the northern Appalachian and eastern midwestern coal regions. The remaining 25 per-

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cent is assumed to be cleaned by the advanced technology being considered for the particular scenario.

The results of these scenarios are presented in Table 14 along with the estimates of further emission reduction which could have been attained with conventional coal cleaning. The SO_2 emission reductions for each case in Table 14 are reductions relative to the as-delivered coal specified in Table 13. The PCC + FCC scenario shows modest additional reductions relative to the case in which all coals are cleaned with conventional technology. Further cleaning by conventional technology would provide 2.0 millon tons of additional reductions, while cleaning according to the PCC + FCC scenario would provide 2.4 million tons. Reduction by the PCC + VFCC and PCC + SCC scenarios would provide for 3.0 million and 3.6 million tons of additional SO_2 emission reduction.

Additional SO_2 emission reductions which can be achieved by any of the advanced coal cleaning technologies is very sensitive to the fraction of coal being processed by a given advanced technology. Increases or decreases in the amount of coal cleaned with advanced techniques will have a corresponding impact on the SO_2 emission reductions.

Conclusions

The annual SO_2 emission reduction which results from the operation of commercial coal preparation plants probably exceeds 2 million tons annually. By up-grading existing plants and by cleaning those medium and high sulfur coals which are currently not washed, it may be possible to achieve an additional 2 million tons SO_2 per year reduction with state-of-the-art technologies. Additional studies to update and validate these estimates are desirable.

Integrated emission control options which incorporated a combination of state-of-the-art physical coal cleaning technology and boiler emission control technologies may offer substantial advantages due to increased flexibility and reduced costs in meeting SO_2 reduction requirements. The multi-stream approach which allows combustion of a deep-cleaned coal product in a boiler without added SO_2 emission control is especially promising. Further studies to assess the potential economic advantages of these integrated emission reduction options are desirable.

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Near-term fine coal cleaning processes may be capable of providing additional reductions in SO_2 emission. However, there is substantial uncertainty regarding the technical effectivenss and costs of these processes for a wide range of coals. If cost effective, this technology would probably be used in conjunction with conventional technology to upgrade the performance in both new and existing plants.

Advanced chemical coal cleaning processes can be used to achieve substantial reductions in SO_2 emission if the processes are capable of removing most of the fine pyrite and a large fraction of the organic sulfur. These processes must be cost competitive with other SO_2 emission reduction methods if they are to be used commercially.

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Notes:

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Notes:

Table of Conversion Factors

Multiply English Unit	by	To Obtain SI Unit
pound (lb)	453.59	gram (g)
ton (2000 lb)	0.907	megagram (Mg) = metric tonne
inch (in.)	0.0254	meter (m)
foot (ft)	3.048	meter (m)
British Thermal Unit (Btu)	1054.88	Joule (J)
Btu/lb	2.326	J/g
lb/10^6 Btu	429.907	ng/J
$/ton	1.1025	$/Mg
$/$10^6$ Btu	0.9480	mill/MJ = 10^{-3} $/MJ
lb/ft^3	0.0160	g/cm^3

Tyler Screen Size Mesh Openings

Mesh Size	Sieve Opening	
	in.	mm
14	0.0469	1.18
28	0.0234	0.60
48	0.0117	0.30
100	0.0059	0.15
200	0.0029	0.075
270	0.0021	0.053
325	0.0017	0.045

Notes:

Table 1: Cumulative washability data for Pittsburgh coal bed, Harrison County, Ohio(a)

Sample Crushed to Pass 1-1/2 In.

	Recovery, %				Sulfur, %		
	Weight	Btu	Btu/lb	Ash, %	Pyritic	Total	lb $SO_2/10^6$ Btu
Float-1.30	35.4	39.2	13925	3.7	0.40	1.73	2.5
Float-1.40	73.8	79.7	13592	6.0	1.01	2.47	3.6
Float-1.60	90.3	96.0	13375	7.5	1.43	2.98	4.5
Float-1.90	93.2	98.0	13231	8.5	1.56	3.12	4.7
Total	100.0	100.0	12580	13.0	2.01	3.48	5.5

Sample Crushed to Pass 3/8 In.

	Recovery, %				Sulfur, %		
	Weight	Btu	Btu/lb	Ash, %	Pyritic	Total	lb $SO_2/10^6$ Btu
Float-1.30	52.5	57.8	13939	3.6	0.32	1.71	2.5
Float-1.40	81.2	88.1	13722	5.1	0.74	2.21	3.2
Float-1.60	88.9	95.1	13534	6.4	0.94	2.44	3.6
Float-1.90	92.4	97.7	13375	7.5	1.11	2.62	3.9
Total	100.0	100.0	12652	12.5	1.89	3.35	5.3

Sample Crushed to Pass 14 Mesh

	Recovery, %				Sulfur, %		
	Weight	Btu	Btu/lb	Ash, %	Pyritic	Total	lb $SO_2/10^6$ Btu
Float-1.30	23.3	26.1	14084	2.6	0.23	1.61	2.3
Float-1.40	78.6	85.9	13751	4.9	0.56	1.99	2.9
Float-1.60	87.3	93.9	13534	6.4	0.77	2.21	3.3
Float-1.90	91.5	97.1	13346	7.7	0.98	2.42	3.6
Total	100.0	100.0	12580	13.0	2.00	3.48	5.5

(a) All values given on a moisture-free basis. The air-dried raw coal moisture content of the original sample was 2.6%. Data from Reference 2.

Table 2: Summary of average physical desulfurization potential of coals by region (2)

(Cumulative analysis of float 1.6 product for 1-1/2 in. top size)

Coal Region	No. Samples	Raw Coal Emission Parameter, lb $SO_2/10^6$ Btu	Float Product Emission Parameter, lb $SO_2/10^6$ Btu	Reduction in Mean, percent(a)
Northern Appalachian	227	4.8	3.2	31
Southern Appalachian	35	1.6	1.3	12
Alabama	10	2.0	1.7	11
Eastern Midwest	95	6.5	4.4	30
Western Midwest	44	9.0	6.1	29
Western	44	1.1	0.9	12

(a) Note that the average percent reduction in the emission parameter is not the same as the percent reduction between the mean raw and the mean product values.

Table 3: Raw and clean coal properties of three northern Appalachian coals by conventional cleaning

	Seam/County, State		
	Pittsburgh/ Harrison, OH	Clarion/ Meigs, OH	Upper Freeport/ Westmoreland, PA
Raw Coal Properties			
Calorific Value[a], Btu/lb	12,580	10,385	11,719
Ash Content, %	13.0	25.5	22.4
Total Sulfur Content, %	3.5	3.5	3.6
Pyritic Sulfur Content, %	2.0	2.1	3.0
Emission Parameter, lb $SO_2/10^6$ Btu	5.5	6.8	6.1
Clean Coal Properties[b]			
Btu Recovery, %	95.0	92.5	90.0
Weight Recovery, %	89.0	77.5	75.0
Calorific Value[a], Btu/lb	13,425	13,395	14,040
Ash Content, %	7.3	11.0	7.0
Total Sulfur Content, %	2.9	2.7	2.0
Pyritic Sulfur Content, %	1.4	1.2	1.2
Emission Parameter, lb $SO_2/10^6$ Btu	4.3	4.4	2.9
Percent Reduction (Increase)			
Calorific Value	(7)	(19)	(20)
Ash Content	44	57	69
Total Sulfur Content	17	23	44
Pyritic Sulfur Content	30	44	60
Emission Parameter	22	36	54

(a) Calorific value on a moisture-free basis.
(b) From coal washability data in Reference 2. Clean coal properties estimated from float product for 1-1/2 in. top size at indicated Btu recovery.

Table 4: Characteristics of major wet-coal cleaning devices

Device	Principle of Separation/ Medium	Sizes Typically Handled	Capacity/ Efficiency	Specific Gravity Range	Comments
Coarse coal jig	Stratification/ water	6 x 1/4 in.	High/good	1.60-1.90	Typically used to clean coarse coal at relatively high specific gravities. Efficiency decreases rapidly at sizes below 1/8 in.
Fine coal jig	Stratification/ water	1/2 in. x 28M	High/good	1.60-1.90	Reported to be as efficient as concentrating tables when handling compatible size. High unit capacity.
Hydrocyclone	Centrifugal forces in ascending vortex/water	1/2 in. x 100M	High/poor	1.60-1.90	Poor cleaning efficiency, but can be used as 'scalpers' ahead of more efficient devices.
Concentrating table	Stratification and hindered settling/water	3/8 in. x 200M	Low/good	1.50-1.80	Provides good separation when near-gravity material is less than 10% of feed. Requires very low water-to-solids ratio.
Heavy-medium vessel	Float and sink/ heavy medium	6 x 1/4 in.	High/exc.	1.30-1.80	Efficiency of separation near theoretical, even when feed contains large amounts of near-gravity material.
Heavy-medium cyclone	Float and sink plus centrifugal forces/heavy medium	3/8 in. x 28M 1-1/2 in. x 0	High/exc. High/very good	1.30-1.80 1.30-1.80	Excellent separating efficiency for 3/8 in. x 28 mesh feed but raw feed must be deslimed.(c) Can replace multiple cleaning circuits using 1-1/2 in. x 0 feed (no desliming needed with some performance loss.
Flotation	Particle attachment/ water	28M x 0 100M x 0	Med./DCP(a) Low/DCP	N/A(b) N/A	Not efffective for oxidized coal and is often inefficient for pyrite removal. More expensive than other cleaning methods.

(a) DCP - dependent on coal properties
(b) N/A - not applicable
(c) Deslime - removal of minus 28 mesh material

Table 5: Advanced physical, biological, and chemical coal cleaning processes

Process and Major Developers	Cleaning Methods	Type of Sulfur Removed	Commercialization Status (Potential)(a)
Advanced Flotation-Dept. of Energy, Penn State Univ., Advanced Fuels Technology	Coal and/or ash floated in cells using micro-bubbles or improved reagents.	Pyritic	N, I
True (or Homogeneous) Liquid Beneficiation-Otisca Industries, Dow Chemical, TRW, American Electric Power	Gravimetric separation using organic fluids or brines.	Pyritic	N, I
Electrostatic Separation-Advanced Energy Dynamics	Electrostatic drum separator for very fine particles. Proprietary process for separation of ultra-fines.	Pyritic	N, I
High Gradient Magnetic Separation-Sala Magnetics, Magnetic Corp. of America, TVA	Separation of paramagnetic mineral particles from organic particles in a high intensity magnetic field.	Pyritic	I, L
Agglomeration-National Research Council of Canada, Otisca Industries, Battelle Columbus, Univ. of Pittsburgh	Form agglomerates of coal in oils, organic liquids, CO_2 (liq.). Size separation of agglomerates from fine mineral particles.	Pyritic	N, I
Chemical-Biological-Ohio State, Lehigh, Penn State, Atlantic Research Corp.	Bacteria selectively oxidizes mineral sulfur and some organic sulfur.	Pyritic and Organic	L
Chemical-Alkali Leaching-"Gravimelt," TRW Inc.	Removal of sulfur by molten alkali hydroxides. Removal of residual ash by weak acid leaching.	Pyritic and Organic	L
Chemical-Microwave-General Electric Inc., TRW	Microwave irradiation of NaOH treated coal. Washing to remove soluble sulfur compounds.	Pyritic and Organic	L

(a) N-Near-term potential. Could be commercial by 1990.
I-Intermediate-term potential. Could be commercial by 1995.
L-Long-term potential. Not available for commercialization until after 1995.

Table 6: Clean coal properties of three coals for multi-stream coal cleaning[a]

	Seam/County, State		
	Pittsburgh/ Harrison, OH	Clarion/ Meigs, OH	Upper Freeport/ Westmoreland, PA
Deep Cleaned Product (DCP)			
Btu Recovery, %	65.0	74.0	76.0
Weight Recovery, %	60.5	56.0	61.0
Calorific Value, Btu/lb	13,720	12,930	14,450
Ash Content, %	5.2	7.0	4.3
Sulfur Content, %	2.2	2.3	1.3
Emission Parameter, lb $SO_2/10^6$ Btu	3.1	3.5	1.8
Middling Product (MP)			
Btu Recovery, %	30.0	18.5	14.0
Weight Recovery, %	28.5	21.5	14.0
Calorific Value, Btu/lb	13,240	8,940	11,720
Ash Content, %	11.9	21.4	18.8
Sulfur Content, %	4.5	3.9	5.1
Emission Parameter, lb $SO_2/10^6$ Btu	6.8	8.7	8.6
Percent Reduction (Increase)			
DCP Calorific Value	(9)	(25)	(23)
MP Calorific Value	(5)	(14)	0
DCP Sulfur Content	38	36	64
MP Sulfur Content	(29)	(10)	(40)
DCP Emission Parameter	43	49	71
MP Emission Parameter	(23)	(28)	(40)

(a) Estimated from washability data in Reference 2. DCP defined by 1.35 s.g. float product at 1-1/2 in. top size. MP defined by mass, energy, ash, and sulfur balances made between DCP and clean coal properties in Table 3. Calorific values on a moisture-free basis.

Table 7: Reblended clean coal properties of three coals for multi-stream coal cleaning(a)

	Seam/County, State		
	Pittsburgh/ Harrison, OH	Clarion/ Meigs, OH	Upper Freeport/ Westmoreland, PA
Deep Cleaned Product (DCP)			
Btu Recovery, %	47.5	46.25	45.0
Weight Recovery, %	44.2	35.0	36.1
Calorific Value, Btu/lb	13,720	12,930	14,450
Ash Content, %	5.2	7.0	4.3
Sulfur Content, %	2.2	2.3	1.3
Emission Parameter, lb $SO_2/10^6$ Btu	3.1	3.5	1.8
Blended Middling Product (BMP)			
Btu Recovery, %	47.5	46.25	45.0
Weight Recovery, %	44.8	42.5	38.9
Calorific Value, Btu/lb	13,340	11,300	13,560
Ash Content, %	9.4	14.3	9.5
Sulfur Content, %	3.6	3.1	2.7
Emission Parameter, lb $SO_2/10^6$ Btu	5.5	5.4	3.9
Percent Reduction (Increase)			
DCP Calorific Value	(9)	(25)	(23)
BMP Calorific Value	(6)	(9)	(16)
DCP Sulfur Content	38	36	64
BMP Sulfur Content	(5)	13	26
DCP Emission Parameter	43	49	71
BMP Emission Parameter	1.3	20	36

(a) BMP determined by blending of MP from Table 6 with DCP coal. Calorific values on a moisture-free basis.

Table 8: Single stream combined SO_2 emission reduction by LIMB and FGD[a]

	Coal Seam					
	Pittsburgh		Clarion		Upper Freeport	
	Ep	%R	Ep	%R	Ep	%R
Raw Coal Emission	5.5	--	6.8	--	6.1	--
Emission after PCC + LIMB	1.7	69	1.7	74	1.1	81
Emission after PCC + FGD	0.4	92	0.4	94	0.3	95

(a) Raw and clean coal properties from Table 3. LIMB assumed to provide 60% emission reduction and FGD 90% emission reduction while using cleaned coal. Emission parameter (Ep) in lb $SO_2/10^6$ Btu, and Ep reduction (%R) in %. %R is relative to raw coal.

Table 9: Potential SO_2 emission and emission reductions with multi-stream combined systems[a]

	Coal Seam					
	Pittsburgh		Clarion		Upper Freeport	
Stream	Ep	%R	Ep	%R	Ep	%R
Deep Cleaned Coal	3.1	43	3.5	49	1.8	71
Middling Stream with LIMB	2.2	60	2.2	68	1.6	75
System Average, MPCC + LIMB	2.7	51	2.8	58	1.7	76
Middling Stream with FGD	0.5	91	0.5	92	0.4	94
System Average, MPCC + FGD	1.8	67	2.0	71	1.1	82

(a) Based on multi-stream data from Table 7. Emission parameter (Ep) in lb $SO_2/10^6$ Btu, and Ep reduction (%R) in %. LIMB assumed to provide 60% emission reduction in cleaned middling stream. FGD assumed to provide 90% reduction in cleaned middling stream. Emission reductions relative to raw coal.

Table 10: Effect of advanced coal cleaning technology on SO_2 emission from three coals[a]

Coal Cleaning Technology	Coal Seam					
	Pittsburgh		Clarion		Upper Freeport	
	Ep	%R	Ep	%R	Ep	%R
Conventional[b]	4.3	22	4.4	36	2.9	54
FCC	3.3	40	4.3	37	1.8	71
VFCC	2.6	53	3.0	56	1.5	75
CCC	1.5	72	1.8	74	0.9	86

(a) Estimated from coal data in Reference 2. Emission parameter (Ep) in lb $SO_2/10^6$ Btu, and Ep reduction (%R) in %.
(b) Comparative conventional technology from Table 3.

Table 11: SO_2 emission reduction using conventional and advanced technology in preparation plant[a]

Cleaning Technologies	Coal Seam					
	Pittsburgh		Clarion		Upper Freeport	
	Ep	%R	Ep	%R	Ep	%R
Conventional (PCC)	4.3	22	4.4	36	2.9	54
PCC + FCC	3.7	34	3.8	44	2.3	62
PCC + VFCC	3.1	44	3.4	50	1.9	69
PCC + CCC	2.7	51	3.2	53	1.7	72

(a) Estimated from coal data in Reference 2. PCC coal defined to have DCP properties in Table 6. BMP in Table 6, cleaned by FCC, VFCC, or CCC to obtain advanced middling product which is blended with DCP to obtain plant product. Emission parameter (Ep) in lb $SO_2/10^6$ Btu, and Ep reduction (%R) in %.

Table 12: Comparison of average percentage SO_2 emission reductions for different coal cleaning options

Strategy	Coal Seam		
	Pittsburgh	Clarion	Upper Freeport
Single Cleaning Technology Plants			
PCC	22	36	54
FCC	40	37	71
VFCC	53	56	75
CCC	72	74	86
Integrated Cleaning Technology Plants			
PCC + FCC	34	44	62
PCC + VFCC	44	50	69
PCC + CCC	51	53	72
Multi-stream Combined Systems			
MPCC + LIMB	51	58	76
MPCC + FGD	67	71	82

Table 13: Estimated SO_2 emission reduction achieved in 1979 by washing utility coal mined in eight states(a)

Region and State	Cleaned Coal, %	SO_2 Content of Coal: As-mined (10^3 ton)	SO_2 Content of Coal: As-delivered (10^3 ton)	SO_2 Emission Reduction: 10^3 ton	SO_2 Emission Reduction: %
Northern Appalachian					
Pennsylvania	37	2,160	1,860	300	14
Ohio	42	3,000	2,670	330	11
Northern West Virginia	48	1,910	1,690	220	12
Southern Appalachian					
Southern West Virginia	48	310	290	20	7
Virginia	30	280	270	10	4
Eastern Kentucky	28	1,650	1,570	80	5
Eastern Midwest					
Western Kentucky	43	2,970	2,600	370	13
Indiana	79	1,760	1,410	350	20
Illinois	82	3,730	2,780	950	26
Alabama					
Alabama	54	480	440	40	8
Eight State Total	48	18,250	15,580	2,670	15

(a) From Reference 15. Data adjusted to reflect improved estimates of the amount of coal washed. State average emission reduction also revised for following states: NWV from 17% to 24%, SWV from 37% to 12%, and VA from 51% to 12%.

Table 14: Estimated SO_2 emission reduction possible by washing all northern Appalachian and eastern midwestern utility coal in 1979

Region and State	SO_2 Reduction Conventional Technology[a] 10^3 ton	%	SO_2 Reduction Near-Term Technology[b] 10^3 ton	%	SO_2 Reduction Advanced Fine Cleaning[c] 10^3 ton	%	SO_2 Reduction Chemical Cleaning[d] 10^3 ton	%
Northern Appalachian								
Pennsylvania	520	28	620	33	720	39	830	45
Ohio	450	17	540	20	640	24	740	28
Northern West Virginia	240	14	280	17	350	21	410	24
Eastern Midwestern								
Western Kentucky	490	19	540	21	650	25	790	30
Indiana	90	6	120	9	180	13	250	18
Illinois	210	8	270	10	440	16	620	22
Total	2,000	13	2,370	15	2,980	19	3,640	23

(a) Based on as-delivered SO_2 emission, state average emission reductions, and fraction of coal washed as determined in Table 13. Total percentage reductions based on $15,580 \times 10^3$ ton emission of as-delivered coal from eight states.
(b) Near-term technology of FCC estimated by 1.6 s.g. separation of 14 mesh top size coal.
(c) Advanced cleaning or VFCC estimated by assuming 90% pyrite reduction and product coal with 4% ash.
(d) Chemical cleaning or CCC estimated by assuming 95% pyrite and 40% organic sulfur reduction and product coal with 4% ash.

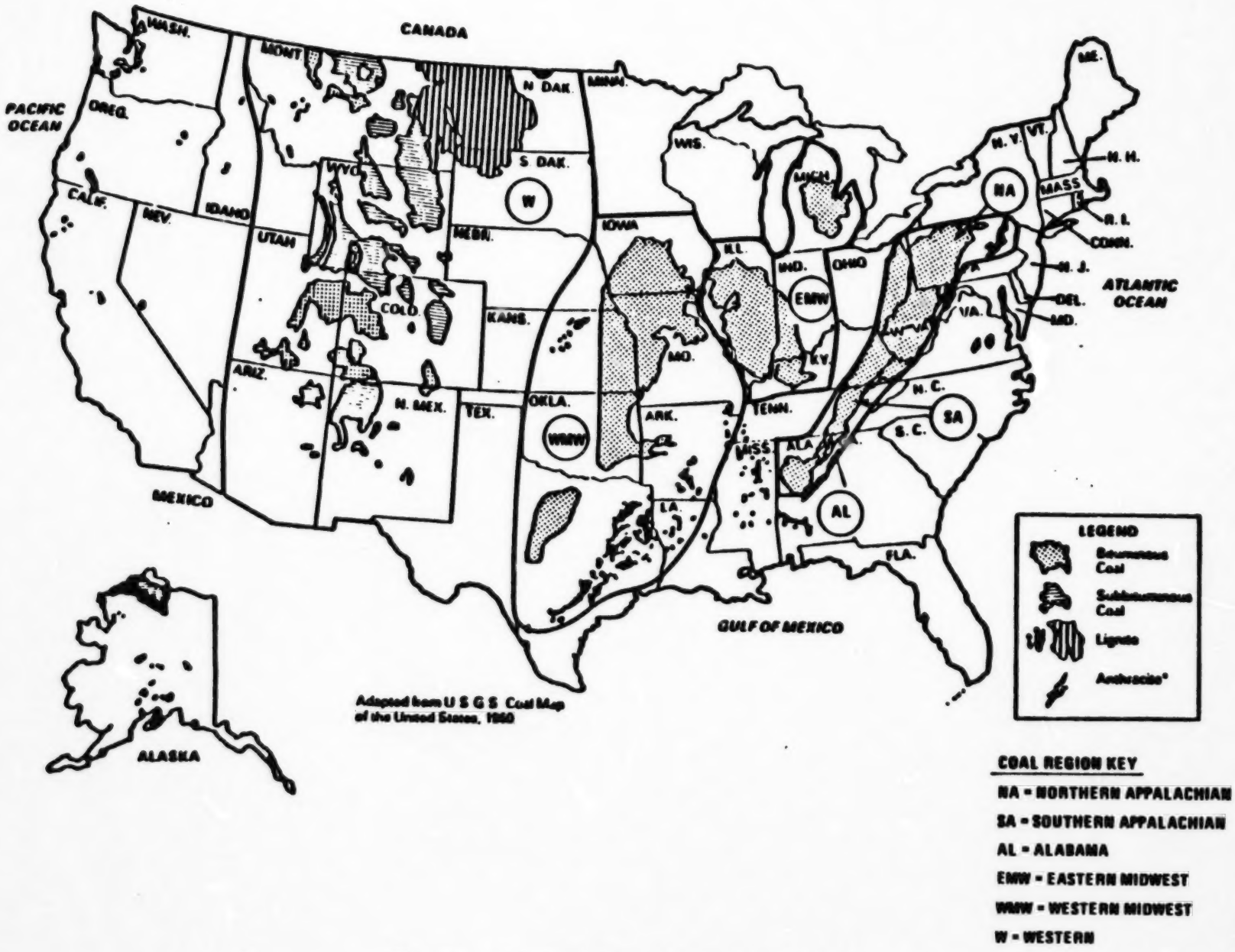

Fig. 1: U.S. coal deposits and coal regions

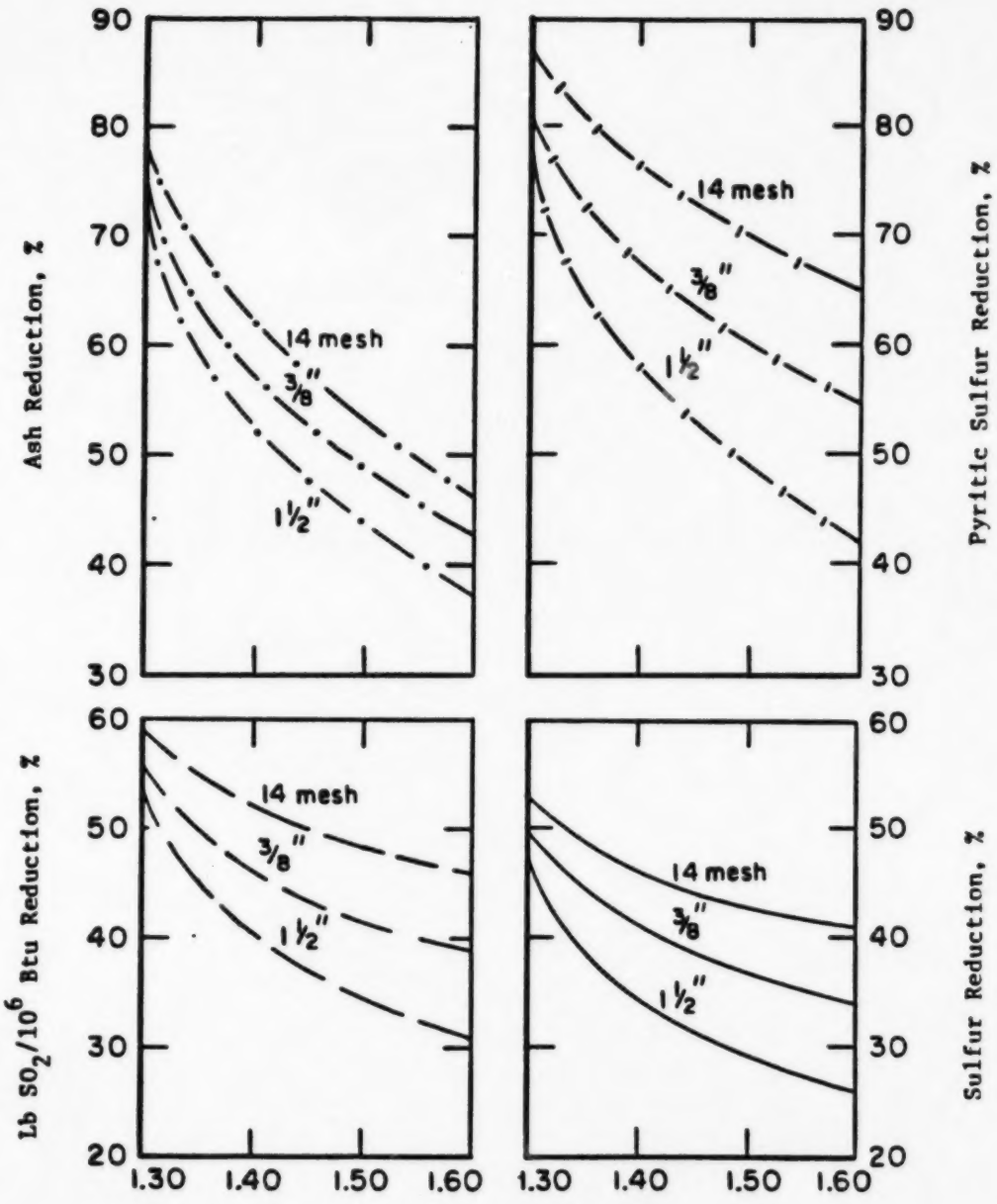

Fig. 2: The effect of crushing top size and specific gravity of separation on the reduction of ash, pyritic sulfur, total sulfur, and lb $SO_2/10^6$ Btu (2)

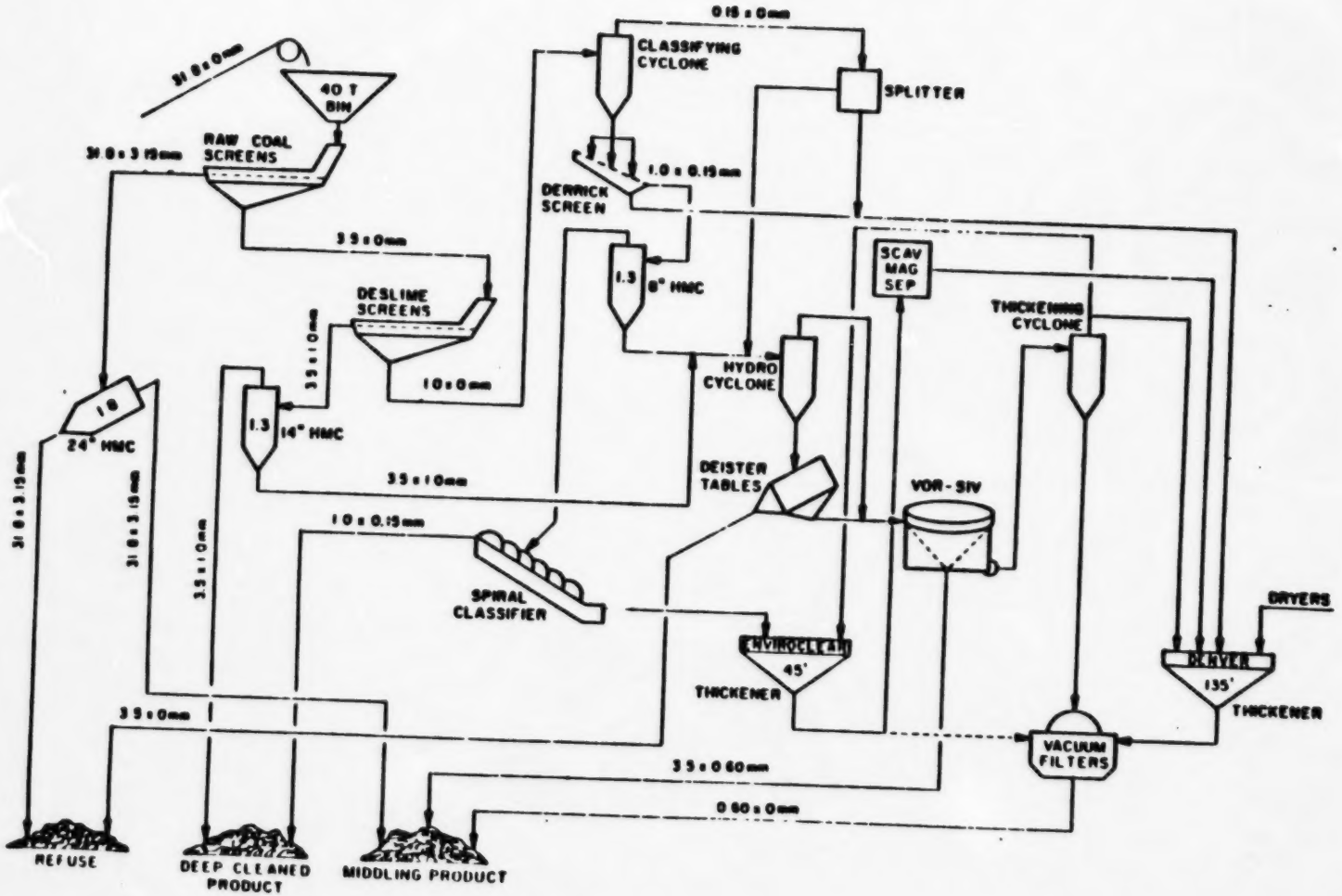

Fig. 3: Level 5 multi-stream coal preparation plant with middling and deep cleaned products[16]

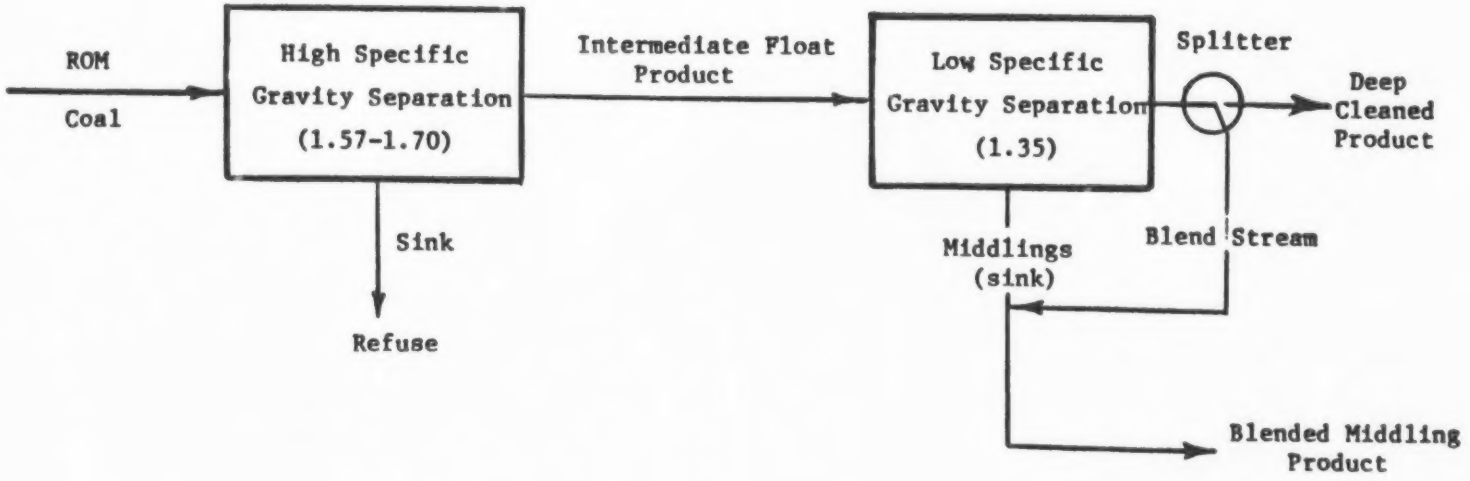

Fig. 4: Simplified schematic of Level 5 multi-product plant

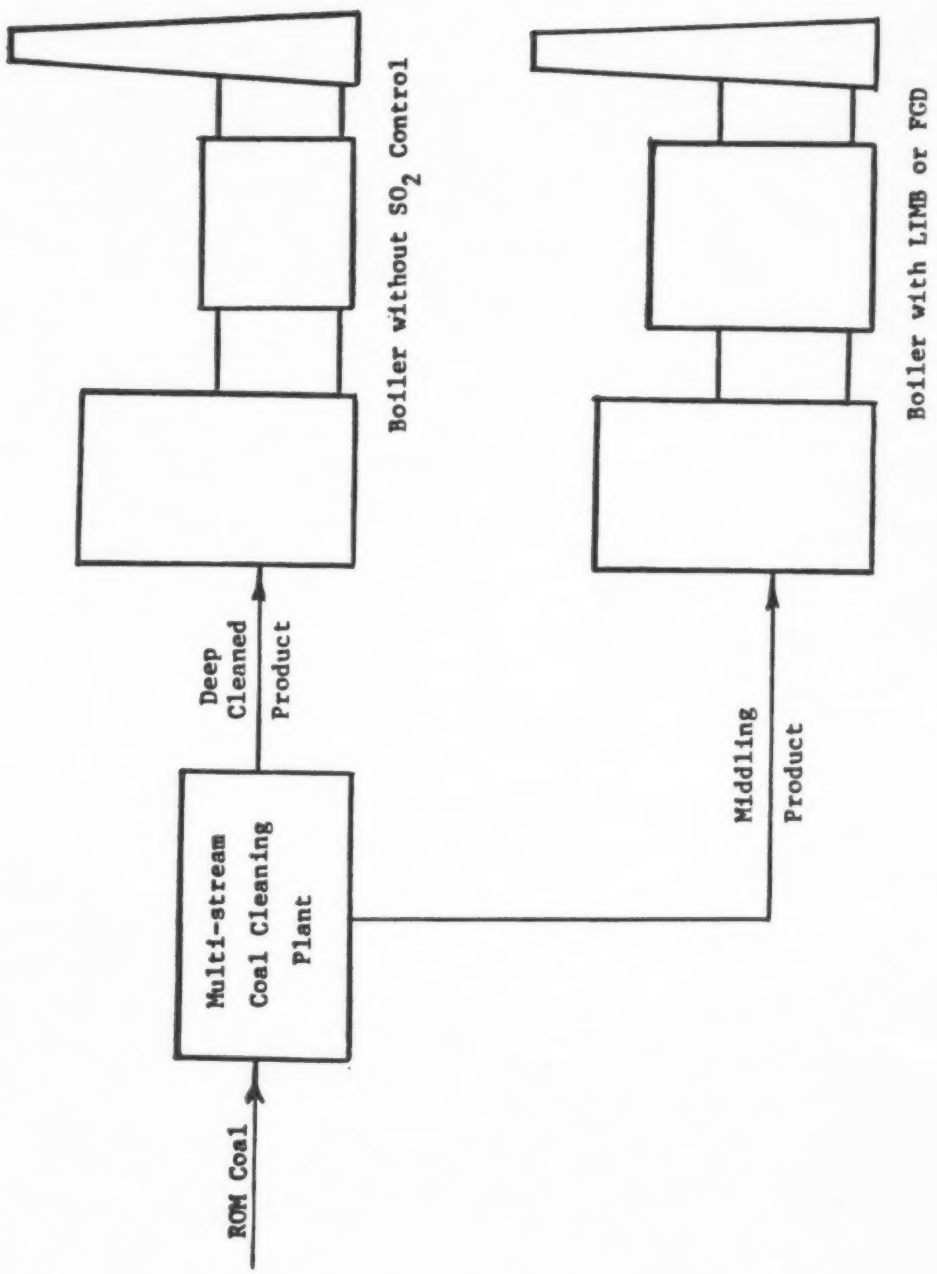

Fig. 5: Multi-stream combined system

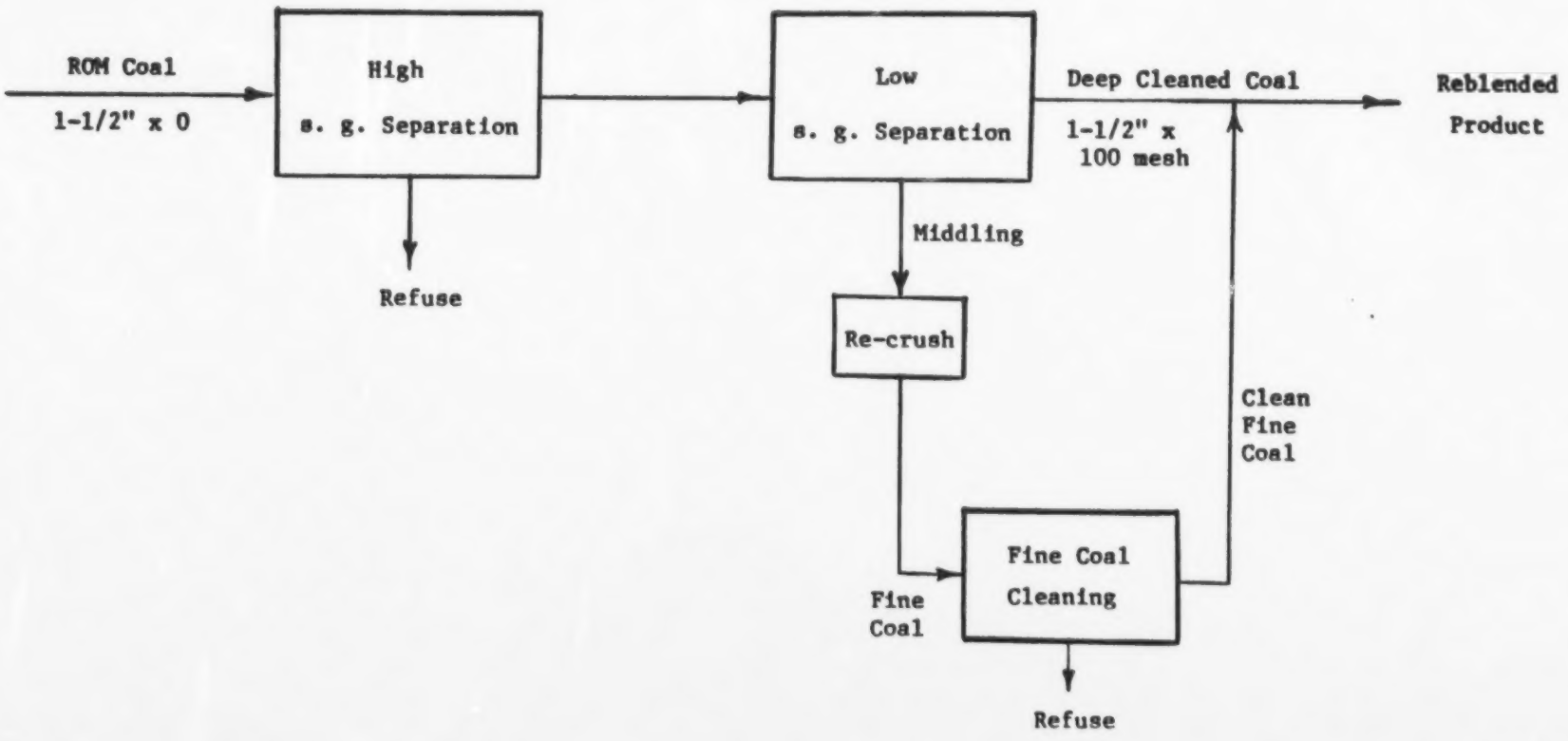

Fig. 6: Schematic of advanced coal preparation plant with conventional and fine coal cleaning